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FORECASTING TYPHOON CHABA'S (2004) INTENSITY CHANGE USING A COUPLED ATMOSPHERE-OCEAN-WAVE MODEL

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1. INTRODUCTION

Recorded 10 typhoons have destroyed many lives of coastal residents on the Japan islands in the 2004 Northwest Pacific typhoon season. Typhoon- and flood-related claims for the fiscal 2004 were 18 times higher than that of the previous year (5 billion dollars). To reduce such disaster risks, an early warning system, which can provide highly accurate information of the track (latitude and longitude of the storm center) and intensity (central pressure, maximum sustained wind speed, and radius of 50kt winds) of an approaching storm, must be implemented and refined.

Several meteorological organizations, JTWC Guam, NHC Miami, CPHC Honolulu and RSMC Tokyo routinely provide first-level basic information of future position and intensity of tropical cyclones in each basin. In recent years, dynamic models of tropical cyclones are generally used for predictions. Although rapid developments of meteorological, remote sensing and computing technologies make it possible to simulate a track of a tropical cyclone with high accuracy, it would be difficult to evaluate the storm intensity even in short-term forecasts because of the following reasons: (1) still lack of spatial resolution in current models, (2) the inadequate parameterizations of key air-sea interaction processes, (3) the inconsistency of the typhoon initialization method using a tropical cyclone bogussing scheme.

The objectives of this study are to develop a high-resolution atmosphere-ocean-wave coupled model for tropical cyclone forecasts over the Northwest Pacific Ocean, and to quantify the impact of complex sea surface processes on Typhoon Chaba's (2004) intensity change, as a case study of a hazardous event which affected the coastal areas of the Japan islands in August 2004.

2. TYPHOON CHABA (2004)

Chaba first reached the typhoon strength around the Marshall Islands on August 19, 2004. The storm moved slowly west and northwest, and the central pressure fell to 910-hPa, and wind gusts were estimated in the excess of 50 m/s on August 25. Landfall was made in the Kyushu islands on August 30. The typhoon brought disaster to the coastal areas in Japan, and it quickly weakened and was turned sharply northeastward and merged with an extratropical system over the Okhotsk Sea.

Figure 1 shows the sea surface temperature (SST) differences between before and after the passage of Chaba, observed by the passive microwave satellite sensors TRMM/TMI and Aqua/AMSR-E. Before the passage, Chaba drew its energy from extensive ocean area with a temperature greater than 29 degree C (not shown). However, the strong storm moving over the warm ocean caused a large SST decrease, reaching a maximum of about 4 degree C likely along and just to the right of the storm track. During the period, Chaba that moved slowly westward experienced the gradual intensity decay, from 910 to 945 hPa. Bender et al. (1993) indicated that such a large SST decrease tends to be produced by a slowly moving storm with a speed of less than 5 m/s.

3. MODEL DESCRIPTIONS

A coupled atmosphere-ocean-wave model (typhoon forecast version) developed in this study is based on three existing models: MM5 with a tropical cyclone bogussing scheme (Dudhia, 1993), CCM (Murakami et al., 2004), and SWAN (Booij et al., 1997). The coupled model simultaneously represents both atmospheric and ocean processes, and interactively exchanges information at the interface among these three model components, at every 10 minutes (see in Figure 2).

MM5 (Dudhia, 1993) is a non-hydrostatic,

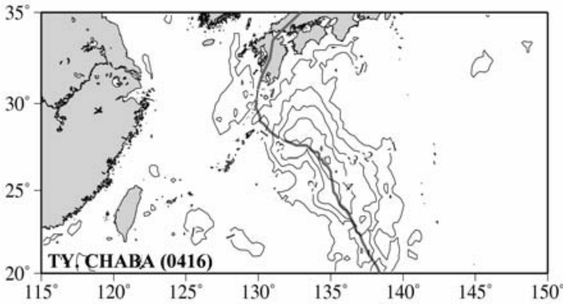

Figure 1: Sea surface temperature difference between before and after the passage of Typhoon Chaba (2004).

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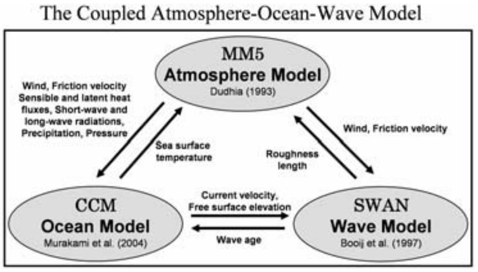

Figure 2: A schematic diagram of the coupled atmosphere - ocean - wave model.

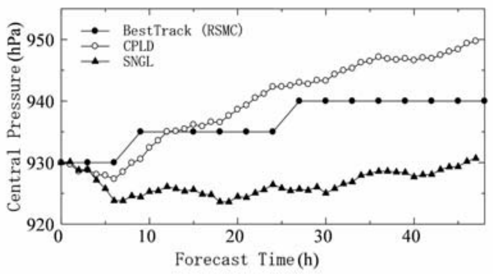

Figure 3: Time series (48 hours) of the minimum surface pressure in observed and simulated storms.

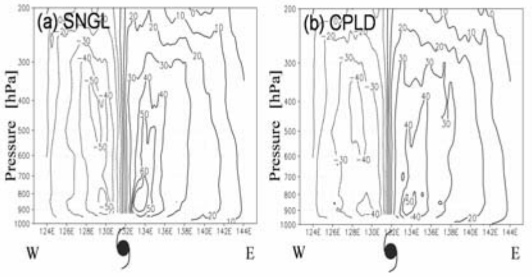

Figure 4: Vertical cross sections of tangential winds in (a) SNGL; and (b) CPLD.

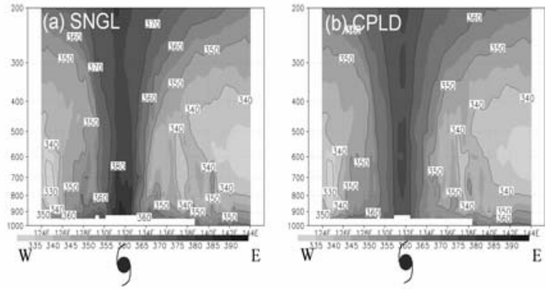

Figure 5: Vertical cross sections of equivalent potential temperature in (a) SNGL; and (b) CPLD.

finite-differencing, terrain-following sigma-coordinate, cloud-resolving primitive equation model, developed by the Pennsylvania State University (PSU) and National Center for Atmospheric Research (NCAR). This model is designed to simulate complex mesoscale meteorological phenomena on the order of a few to several hundred kilometers. Specific physical parameterizations for this simulation include the Mellor-Yamada level 2.5 PBL scheme (Janjic´, 1994), the Grell (1993) cumulus parameterization, and an explicit cloud microphysical scheme (including separate treatment of cloud water, rain, cloud ice, and snow) implemented by Reisner et al. (1993).

CCM (Murakami et al., 2004) is a multi-sigma coordinate coastal current model originally developed by the authors, and is composed of momentum, mass, temperature, salinity and density equations and is closed mathematically with the Mellor and Yamada level 2.5 turbulent closure scheme. The vertical multi-sigma coordinate approach allows to realistically simulating 3-D coastal ocean flow and water quality from deep to shallow water.

SWAN (Booij et al., 1997) is a sophisticated third-generation time-dependent spectral wave model designed for the near-shore zone and can effectively simulate wave generation and propagation due to local winds, as well as wave transformation processes due to refraction, shoaling, current blocking, whitecapping, wave breaking and bottom friction.

The coupled model was run with horizontal grid spacing of 10 km for MM5 and 14 km for CCM and SWAN, which cover a 2000x2000 km wide region that contains the nearshore waters of the Japan islands. The forecasting period is 48 hours from 1200 UTC 27 through 1200 UTC 29 August in 2004, when Typhoon Chaba gradually got weaker before its landfall (see in Figure 3). Initial and boundary conditions are taken from NCEP final analyses (1 degree resolution) for MM5, JCOPE ocean analyses (10 km resolution) for CCM, and steady-state values diagnosed by the initial wind field for SWAN. The best track data reported by the Japan Meteorological Agency was applied for the typhoon initialization.

4. RESULTS AND DISCUSSION

We have conducted two types of sensitivity experiments: 1) using the coupled model developed in this study (CPLD), and 2) using a single MM5 model (SNGL). Figure 3 compares the time series of the minimum surface pressure between simulated and observed storms. There is a large difference in the typhoon evolution between these two models. The typhoon intensity in CPLD varies from 930 hPa to 950 hPa during the 48 hours integrations, similar to that of the actual typhoon. In contrast, the SNGL storm sustains the strength (about 930 hPa) during the simulation. The result indicates that the difference in the treatment of sea surface processes is considered to lead to be a crucial error (-20 hPa in this case) in a tropical cyclone intensity forecast.

The typhoon-associated tangential wind fields, given in Figures 4a and 4b, show a large difference between both simulations. It is evident that the eyewall wind speed profiles in SNGL become more intense, more compact, and more symmetric than

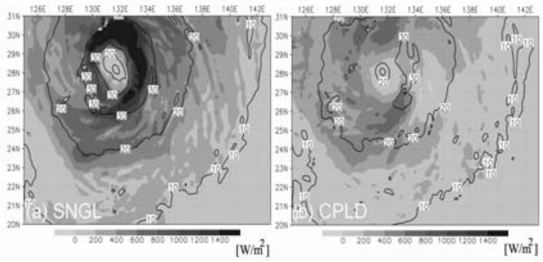

Figure 6: Horizontal distributions of surface wind speeds (solid line) and latent heat fluxes (shaded) in (a) SNGL; and (b) CPLD.

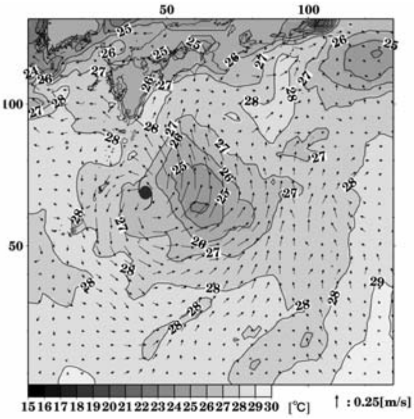

Figure 7: A horizontal distribution of sea surface temperature (shaded) and surface current (vectors) in the ocean model.

those in CPLD. The peak tangential wind increases from 50 m/s in CPLD to 60 m/s in SNGL. Figures 5a and 5b are the equivalent potential temperature fields in both cases, showing typhoon warm core structures. The low-level temperatures in the SNGL eye are approximately 10 K warmer than those in the CPLD eye. It is considered that the strong storm in CPLD is developed by diabatic heating and moistening over the warm ocean. Similar comparative features can be seen in the profiles of the other variables, potential vorticity, humidity and cloud/precipitation (not shown). The SNGL storm seems to be excessively strong and extremely reinforced (i.e. an erroneous forecast).

In order to examine the mechanisms contributing to the differences of storm intensity in these two experiments, let us consider here the energy inflow into the typhoon core. Figures 6a and 6b display the distributions of the latent heat flux at the sea surface in SNGL and CPLD, respectively. In SNGL, the evaporation rate (over 1400 W/m^2) is much larger than that in CPLD (600-800 W/m^2), and shows more symmetric “ring” distribution around the eyewall. The sensible heat flux distributions also show the similar patterns, but the effect is secondary importance (not shown). The more intense surface total fluxes in SNGL are also consistent with the low-level strong warm core formation, as shown in Figure 5a. The results suggest that excessively high evaporation (heat transfer) rate is attributed to a strong positive feedback cycle and the positive typhoon intensity bias. In addition, it should be emphasized that the reasonable parameterization of the atmospheric -ocean-wave interaction is quite important and essential for a typhoon intensity forecast.

Finally, the upper ocean response induced by the CPLD storm is discussed in Figure 7. The rapid cooling of the sea surface (about -5 K) occurs at the east of the Chaba’s center, where a strong southerly wind induces strong turbulent mixing. According to the ocean model output, the shallow mixed layer depths and strong stratification, which are favorable conditions for cooling of sea surface temperature, were promoted by the resultant vertical advection of cold water from below due to the Ekman pumping just beneath the slow moving typhoon. The results imply that in order to predict the realistic typhoon intensity, the full 3-D ocean model, rather than a 1-D mixed layer model generally often used, must be applied to a coupling model.

5. CONCLUSION

In this study, the coupled atmosphere-ocean-wave model was developed for typhoon early warning. The ocean coupling had an important effect on storm intensity. Inclusion of the ocean surface processes was found to be important to reduce the positive intensity bias during the forecast when the typhoon was greatly impacted by the reduced, reasonable supply of heat and moisture.

Of course, this coupled model can directly provide early warning information not only about future position and intensity but also about the hazard of typhoon-related disasters (high wind, storm surge, and high waves) along coastal areas.

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